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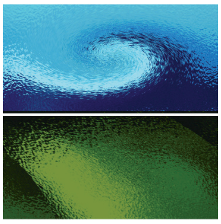

RESEARCH ARTICLE

Challenges for applying vulnerability assessments in coastal lagoons

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Abstract

Here I discuss how vulnerability assessment could be used for coastal lagoons. However, this has to take into account that many coastal lagoons have already been impacted by other forcings, like eutrophication. Vulnerability is not a well-defined concept in mainstream ecology and as a result, ecologists are poorly prepared to address vulnerability assessments. I make some proposals on how ecologists could define and use vulnerability in ecology and how ecologists can make pertinent contributions to vulnerability assessments in a multidisciplinary setting. Accordingly:

1- vulnerability can be applied to systems of different levels of integration in biology and ecology.

2- vulnerability is the risk that individuals, populations, species and ecological systems can be harmed, severely damaged or destroyed by environmental hazards and long-term environmental changes, while the intensity of the vulnerability could accommodate for a description of the extent of the impacts and their reversibility or irreversibility.

3- adaptation is a key concept in vulnerability assessment, which distinguishes it from the preceding approaches like impact and risk assessments

4- approaches and concepts, like "Desired States" and trajectories appear very useful in this context particularly if the management needs to target both the improvement of current situation and the vulnerability to environmental change.

Keywords: : Coastal lagoons, vulnerability assessment, environmental hazards, environmental changes

Introduction

Ecologists are increasingly requested to study the "vulnerability" of the ecosystems of their study choices. Coastal lagoon ecosystems are considered particularly vulnerable to climate chance and seawater level rise. As a consequence of the predicted seawater-level rise, the geomorphology and hydraulics of coastal lagoons will be directly affected and some lagoons may even disappear in the near future.

The impact on lagoon systems is further exacerbated by increasing human impact, due to increasing population densities and increasing economic activities in the coastal zone (Millenium Ecosystem Assessment, 2005a).

Political and public awareness in society, which has mainly been promoted through the activities and reports of the Intergovernmental Panel on Climate Change (IPCC), now results in research calls that mandate for so-called "vulnerability assessments". However, in contrast to e.g. geomorphologists, today most ecologist are still poorly prepared with theoretical bases and do not have a pertinent conceptual framework to contribute effectively to the requested analyses of vulnerability. Although the word vulnerability is appealing to ecologists, it does not yet belong to a generally accepted conceptual framework in ecology, which is in contrast with the concepts of stability and resilience. In the past, the use of the term "vulnerable" in ecology was used in relation to extinction risks; hence a vulnerable taxon has been defined as a taxon that may become endangered in the near future as defined by the Oxford Concise Dictionary of Ecology (Allaby, 1994).

The situation is further complicated for the ecologists by the fact that it is now generally recognised that vulnerability assessment of ecosystems should not be a mono-disciplinary exercise (Patt *et al.*, 2009). In this paper I discuss the meaning that one could give to the term "vulnerability" in ecology and how ecologist can contribute to the multidisciplinary vulnerability assessments.

Meaningful use of the term "vulnerability" in ecology

So far, no clear and widely accepted definition of vulnerability is available in mainstream ecology. This point is illustrated by the fact that the glossaries of major influential textbooks in ecology (e.g., Odum, 1971; Begon *et al.*, 1990; Levin, 2009) do not define the term "vulnerability". This is in clear contrast with the thoroughly discussed terms of "stability", "resilience" and "resistance" that are, nowadays, key concepts in theoretical ecology.

Nevertheless, a web search using the words "vulnerability", "resilience" and "stability" as the topic of publications in ecology returned 503, 550 and 1,950 publications, respectively (period 1991-2010, Web of Science). Hence the term "vulnerability" seems as popular as "resilience" and it has been assumed that both terms have equivalent meanings.

I will discuss below that this is not the case. In the past, the use of the term "vulnerable" in ecology was used in relation to extinction risks, and a vulnerable taxon has been defined as a taxon that may become endangered in the near future (Oxford Dictionary of Ecology, 1994).

In vernacular language the word "vulnerable" is related to a state of 1) being capable of being wounded or hurt, 2) open to temptation, and 3) exposed to attack. These definitions are clearly referring to human individuals or human communities. It is difficult to transpose them as such to plant and animal communities.

However, the field of applications are broadening and the meanings given to this word are evolving as is illustrated by the evolving text in the Wikipedia on-line free encyclopaedia (http://en.wikipedia.org/wiki/Vulnerability). For common applications, Wikipedia (accessed March 2011) describes vulnerability with a first phrase as "In relation to hazards and disasters, vulnerability is a concept that links the relationship that people have with their environment to social forces and institutions and the cultural values that sustain and contest them". This is a still a merely anthropocentric application. However, later it also states "It's also the extent to which changes could harm a system, or to which a community can be affected by the impact of a hazard.

In global warming, vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. I think that while the first phrase comprises the germs for a workable definition for applications in ecology, the latter phrase sets the stage for the vulnerability assessments in global change research. Hence, I think that in ecology the term should refer to a risk of damage.

This is different from the concept of "resilience" that relates to the shape of the trajectory of an ecological system upon a perturbation and quantifies how quickly it returns to the trajectory of the non-perturbated system. I think that vulnerability can be applied to systems of different levels of integration in biology and ecology. Hence, one could describe the vulnerability of 1) individuals, populations and species, 2) communities and biocoenoses, 3) habitats.

I thus propose as a definition for vulnerability in ecology: the risk that individuals, populations, species and ecological systems can be harmed, severely damaged or destroyed by environmental hazards and long-term environmental changes.

In addition, a description of the intensity of the vulnerability could accommodate for a description of the extent of the impacts and their reversibility or irreversibility. Thus, while vulnerability and resilience are clearly different concepts they can be related to each other only by considering the reversibility or irreversibility of the system.

Accordingly, a low resilience will correspond to a high intensity of vulnerability, and a high resilience with a low intensity of vulnerability. Nevertheless, this does not consider the change of the hazard occurring, which is included in the concept of vulnerability but not in resilience.

The study of the vulnerability of species is highly pertinent global change research and the Millenium Ecosystem Assessment has reported that recent past extinction rates are three orders of magnitude higher than those documented for the distinct past in the geological record and that future extinction rates may increase again an order of magnitude (Millenium Ecosystem Assessment, 2005b). Thus, coastal lagoon ecologists have to consider that species compositions are likely to change in the near future and that community assembly processes will be impacted by decreasing regional species pools (Mouillot, 2007).

Considering vulnerability at the level of the individual may be clarifying when discussing ecological processes and ecological strategies of species. An example is given for bacterial cells in the plankton of coastal lagoons (Maurice *et al.*, 2011), which compared the impact of viral life cycles on bacterioplancton. A planctonic bacterial cells is susceptible to become eliminated by zooplankton grazing and by lytic viral infection, i.e., the individual cell is vulnerable to these processes (see Figure 1). However, in addition to the lytic cycle, some viruses induce a lysogenic cycle, during which the viral genome integrates into the host genome

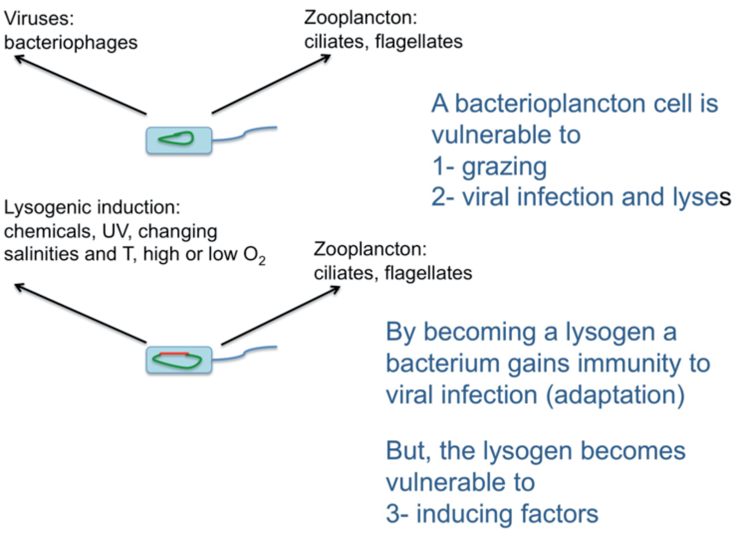

Figure 1. Vulnerability applied in ecology at the level of the individual, example of a bacteriplancton cell.

and remains as a prophage within the host bacterium called a lysogen. Several studies (references cited in Maurice *et al.* 2011) have shown that a lysogen is immune to infection by viruses that are phylogenetically related to the prophage, although the lysogen is vulnerable to inducing factors like toxic chemicals, UV radiation and varying salinities. Hence, the reduced vulnerability to lytic infections has a trade-off for the lysogen, because it has become vulnerable to these inducing factors. Indeed Maurice *et al.* (2011) detected lysogeny in four out of ten French coastal lagoons with a frequency of inducible lysogens ranging from 24 to 52 % of total bacterial populations.

Considering vulnerability at the community and biocoenoses levels is particularly pertinent when considering potential regime shifts. Examples of regime shifts in coastal lagoons are the sudden shift from a phanerogamme dominated benthic community (*Zostera* and *Ruppia* species) to a community of floating opportunistic macroalgal species (e.g., *Monostrome* and *Ulva*). Such regime shifts have been attributed to increased eutrophication and the abruptness and non-linearity can be the consequence of ecological and biogeochemical interactions that give rise to threshold effects. Thus whence the threshold has been exceeded the biocoenoses flips over to a new state (e.g. De Wit *et al.*, 2001; Viaroli *et al.*, 2008). However, in some cases the occurrence of positive feedback loops in the ecological interactions may give rise to the existence of a window of environmental conditions for which two or more alternative stable states exist (Lewontin, 1969; Van de Koppel *et al.*, 2001; Petraitis and Dudgeon, 2004; Yamamuro, 2012). For this case it may be particularly pertinent to consider the vulnerability of the different stable states to other perturbations or stressors. Hence it has been proposed that the phanerogam dominated state, while it still represents a stable state at intermediate eutrophication charges, may be susceptible to a flip-over to a macroalgal dominated state (see Figure 2) by an additional stressor. This has been reported for herbicides, which have been extensively used in rice culture in the watershed of Japanese coastal

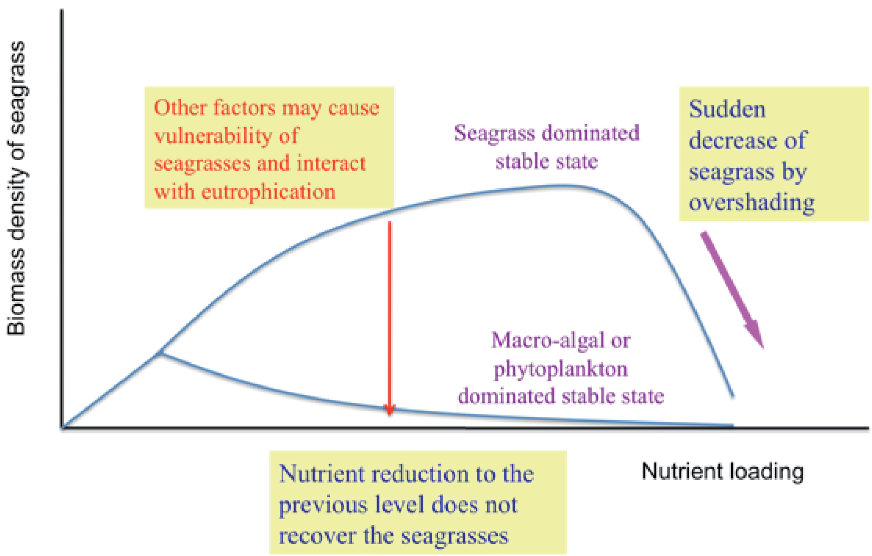

Figure 2. Vulnerability of Ecosystem states. When multiple stable states exist, the biocoenoses may become vulnerable to additional stressors. This example mentions how a seagrass dominated stable state may be vulnerable and potentially flip over to the other stable state dominated by opportunistic algae.

lagoons (Yamamuro, 2012). Thus the use of vulnerability may be particularly important when considering multiple stressors. Finally, at the land and seascape level, an ecologist studying coastal lagoon ecosystems should be aware of the vulnerability of habitats. For example, rising sea-levels and increasing erosion of lido's and barrier islands may result in complete disappearance of the lagoon at the land and seascape level, as the lagoon may be converted to an open bay. In other cases, the lido and the water body of the lagoon may move inward and a lagoonal setting remains possible in the future. Inward moving of lagoons is a natural phenomenon during periods of seawater level rise. However it depends a lot on the geomorphological and physical conditions in the land and seascape. Inward moving is often hampered by man-made structures to protect the land from erosion and and/or flooding and by urbanisation of the shoreline both at the seaside and interior shore of the lagoon. However, natural structures like cliffs may also limit the inward move of lagoons in some specific landscapes. Thus, the surfaces of coastal landscape surface in general and coastal lagoons in particular may become reduced by squeezing between an inward advancing shoreline and fixed boundary inland, a phenomenon referred to as coastal squeeze (Doody, 2004).

In conclusion, it is useful to adopt the term or concept of "vulnerability" in ecological research when a risk of damage or death (extinction) needs to be described for 1) individuals, 2) populations, 3) species, 4) communities and biocoenoses and 5) habitats in landscapes. So far, no clear widely accepted definition of vulnerability is available in main-stream ecology and a non-critical "trendy" use of this word in ecology introduces the risk of using a "buzz" word. I made a proposal for a definition that could be operational and useful in ecology (see above). This needs to be further discussed by the scientific community. I think that ecologists can also make meaningful contributions to vulnerability assessments that have been developed by other disciplines and will be discussed below.

Vulnerability assessments in a multidisciplinary setting

The field of vulnerability assessment has been particularly promoted by the IPCC, which in its Third Assessment Report (IPCC, 2001) called for changing the classical approaches used for impact and risk assessment into a more comprehensive approach that also considers the capacities for adaptation of human societies to climate change. Vulnerability assessment is historically rooted in 1) impact assessment, 2) risk hazard research and 3) food security studies (Patt *et al.*, 2009) and thus draws on various disciplines. Ecologists have traditionally contributed to impact assessments. A classical ecological approach would focus on how a specific scenario of environmental change would impact on the structure and functioning of the ecosystems. In contrast, a vulnerability assessment will also take into consideration that the socio-economic-ecological system has some capacity to adapt, implying that ecosystems can be managed to set off (mitigate) the impact of climate change. Vulnerability assessment is based on a common methodology that integrates the pertinent environmental, economic and social aspects in a coherent framework. As such, assessment is not considered as fundamental scientific research, but rather as an approach of evaluating based on scientific data and reasoning with the aim to synthesize the important existing data and gain knowledge for decision makers and stakeholders (Patt *et al.*, 2009).

The different EU framework programmes for Research and Innovation have financed several collaborative research projects focused on vulnerability assessment. The project titled "Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Sea-Level Rise" (DINAS-COAST) described by Hinkel and Klein (2009). DINAS-COAST was specifically designed to assess the vulnerability of coastal areas to sea-level rise. It comprises a global database of natural system and socioeconomic factors, relevant scenarios, and calculation modules integrated in the DIVA tool. Factors that are considered include erosion, flooding, changing salinities and wetland loss. Unfortunately, the DIVA Tool is currently not available for download (http://www.diva-model.net/).

Adaptation is thus a key concept in vulnerability assessment, which distinguishes it from the preceding approaches. Adaptation (A) has been defined by Metzger *et al.* (2008) as the adjustment in natural or human systems to a new or changing environment. Before considering adaptation, the vulnerability assessment evaluates the Exposure and Sensitivity of the ecosystems using an approach similar to impact assessment. Thus, Exposure defines the nature and the degree to which ecosystems are exposed to environmental change and relies on scenarios for future predictions. The Sensitivity is the predicted impact of these environmental changes on the ecosystem. It has also been defined as the degree to which the human environment is affected, either adversely or beneficially, by environmental change (Metzger *et al.*, 2008) in order to accommodate for the societal impacts as well. Based on the assessment of Exposure and Sensitivity, the approach evaluates the Potential Impact (PI) as a comprehensive description of all impacts that may occur, given projected environmental change, without considering adaptation measures by human societies. Subsequently, the vulnerability assessment explores the theoretical possibilities for such adaptation measures and defines the Adaptive Capacity (AC) as the potential to implement adaptation measures and their potential mitigating effects. Planned Adaptation (PA) relates to the choices that have been put into practice by human societies or will be realised in the future, based on their desires and available resources. PA can thus be defined as the (expected) result of deliberate policy, based on awareness that conditions have changed or are about to change, and that action is required to return to, maintain or achieve a desired state (Metzger *et al.*, 2008). Residual Impact (RI) is defined as the impacts of environmental change that would occur after planned adaptation. Last but not least, vulnerability assessment heavily relies on participative approaches involving different stakeholders (De La Vega-Leinart and Schröter, 2009). This set of definitions illustrates how closely the different disciplines including global change research, geomorphology, ecology, economy and other social and human sciences need to be imbricated for a meaningful vulnerability assessment.

The Planned Adaptation refers to a so-called "Desired State" for the ecosystem. The concept of a "Desired State" is very useful for participative approaches as it invites the stakeholders to discuss their desires for the composition and functioning on the ecosystem in view of the benefits that the different stakeholder groups could obtain from the ecosystem services and invites for searching for consensus. It thus stimulates to think in terms of trajectories for the ecosystem. As a result from discussions among the stakeholders a "Desired State" for the ecosystem can be defined that includes a detailed description as how the stakeholders envision the optimal ecosystem state in view of socioeconomic and environmental targets defined for the future. Very often, we can expect that such a Desired State represents an improvement of the ecosystem state with respect to the current situation, either based on objectively defined criteria but it can also be based on a more subjective perception shared by the stake-holders. Particularly, EU Directives, including the Water Framework Directive (WFD) and Habitat and Birds Directives, which include an obligation for results, imply for many lagoon ecosystems that the current situation is not satisfactory and that ecological status needs to be improved. The concept of a "Desired State" is also implicit in the field of restoration ecology (Clewell and Aronson, 2007) where it is defined as the "Restored State". The particularity of the field of restoration ecology is that this desired restored state is based on targets defined from a historical reference state. This approach is clearly implicit in the WFD, which mandates for defining reference states for the different aquatic ecosystem and poses the targets for "Good Ecological Status" (e.g. Zaldivar *et al.*, 2008).

The problem is that both the WFD and the field of restoration ecology in general have often not considered the impact of global change on the sustainability of the desired and restored states. Only one key publication in restoration ecology (Harris *et al.*, 2006) addresses the implications of climate change for the broader practice of ecological restoration and recognises that restoring historical ecosystems is unlikely to be easy, or even possible, in the changed biophysical conditions of the future. This seems particularly pertinent for the coastal lagoons that are exposed to changes in temperature, precipitation regimes together with increasing seawater-level rise with strong impacts on the hydraulic regimes. In addition, the environmental changes on lagoon systems is further exacerbated by increasing human modifications of environmental conditions due to increasing population densities and increasing economic activities in the coastal zone (Millenium Ecosystem Assessment, 2005a).

Figure 3 depicts the theoretical trajectories of

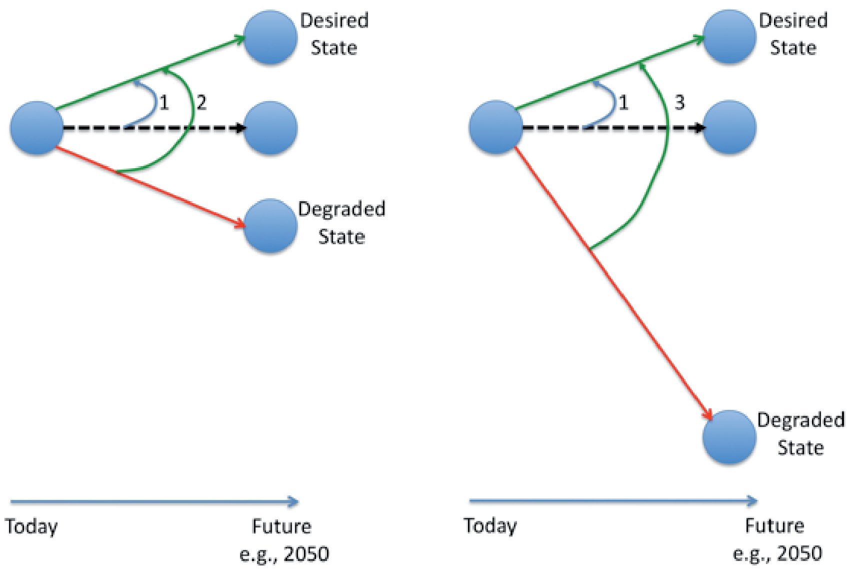

Figure 3. Ecosystem trajectories in time considering a "Desired State". Blue circles represent Ecosystem States for Lagoons and a projection for the future based on scenarios for global environmental change and changing social economic drivers (mainly urbanisation, industrialisation). This presentation draws on concepts and methods used in the discipline of restoration ecology. Two cases are presented, a) left-hand for a scenario of moderate changes in environmental conditions, b) right-hand for a scenario of strong changes.

ecosystems in coastal lagoons facing global change, which integrates my opinion that it will not be possible to maintain the actual state of the ecosystem (broken line) for a "business and management as usual" practice, because of the changing pressures (climate change, sea-level rise and socioeconomic developments). Rather, it is expected that vulnerability of the natural system will increase in view of these pressures and that maintaining "business and management as usual" practice will result in Degraded States of the ecosystem. This can be rephrased according the concepts of the vulnerability analysis. Thus, according the specific scenario (left-hand or right-hand) it will predict large probabilities of degradation, hence it can be predicted that most likely the ecosystem state will be degraded in the future. Notice that for the left-hand scenario of moderate environmental change we can expect a slight degradation (left-hand), while we can expect a very strong degradation for a scenario of strong changes (right-hand). Current management based on the aim of achieving the defined "Desired State" has a tendency to neglect a predicted degradation in the case of a "business and management as usual" practice. It will consider a management effort as indicated by 1) in Figure 3. But, without taking into account changing future pressures, the management effort will not be successful. As a matter of fact the management should take both into account an effort typically requested for improving the ecosystem state and efforts to cope with, adjust and adapt for the changing exogenous pressures (climate change and socio-economic developments) as indicated by 2 and 3. Note that a much more substantial management effort is requested for the right-hand scenario (cf. 3 with 2 in Figure 3).

Figure 4 shows how this abovementioned approach based on predicting trajectories of ecosystem in the context of global change (cf. Figure 3) can be placed in the context of vulnerability assessment. Again I use the definitions proposed by Metzger *et al.* (2008) for the vulnerability assessment. Accordingly, the difference between the current ecosystem state and the degraded state in the future would correspond to the Potential Impact (PI). A modification has to be made to accommodate the management objectives for coastal lagoons where the "Desired State" most often corresponds to an improvement with respect to the current ecosystem state. Therefore, I now introduce the notion of a "Targeted Improvement" (TI), which represents the difference between the current situation and the desired state. It is acknowledged that most often the desired state cannot be achieved and, therefore, an Achievable State must be recognised. This "Achievable State" is now slightly different from the way it is used in classical vulnerability analysis as it is the final result of PA, i.e., planned action that now integrates two objectives namely i) targeting a "Desired State" (PA'1) and ii) adapting to global change (PA'2). As a result, we now also have a slightly different notion of the Residual Impact described as RI' describes the difference between the "Desired State" and the "Achievable State.

In conclusion, I highlight that ecologists can make useful contributions to vulnerability assessments. Particularly, for coastal lagoons, the contributions of the ecologists are absolutely essential in the context of global environmental change. However, the ecologists have to realise that they cannot perform vulnerability assessments alone as a mono-disciplinary exercise. But, rather ecologists need to collaborate closely with their colleague scientists from natural sciences (climate science, geomorphology, physics, chemistry, hydrology as the main disciplines) and socioeconomic sciences (environmental economics, sociology, geographers) as well as with the stakeholders. Some approaches and concepts, like "Desired

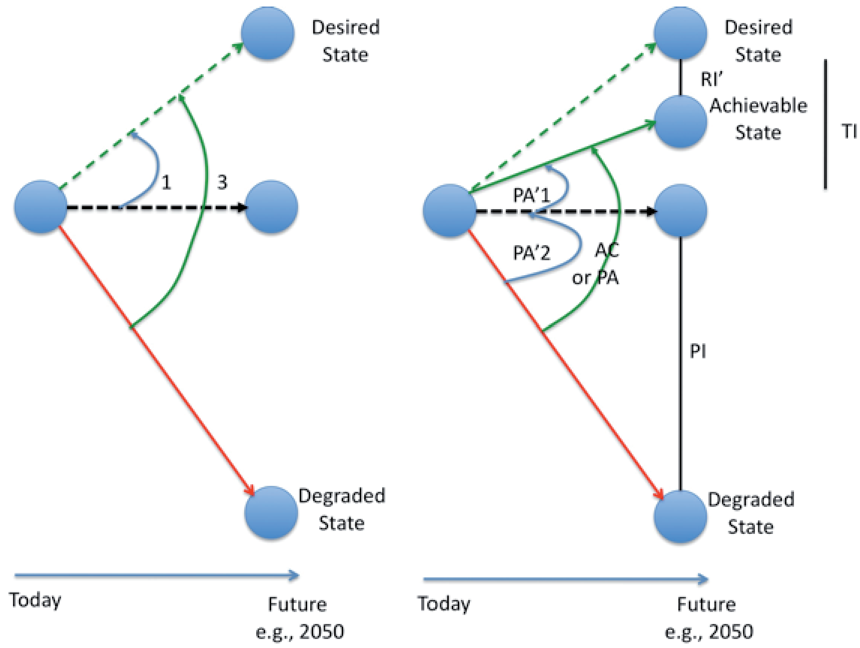

Figure 4. Combining the concepts of "Desired State" and "Degraded State" with the concepts of the Vulnerability assessment (sensu Metzger et al., 2008; IPCC, 2001) requires the recognition of an "Achievable State". It can either be either a "Potential Achievable State" considering that the "Desired State" is the target and that the adaptive capacity AC is employed to its full potential; or it can be studied for a concrete case with a defined PA planned adaptation. PI potential impact would be the difference of the current state to the Degraded State (fully coherent with VA). RI' residual impact is the difference between the "Desired State" and the "Achievable State" which is now slightly different from the way it is used in vulnerability analyses as it is the final result of PA (planned action that now integrates 2 objectives namely targeting a "Desired State" (PA'1) and adapting to global change (PA'2) and vulnerability. To reconcile all ideas I now introduce the notion of TI = targeted improvement (with respect to current situation). Notice that (PI + TI)- RI now represents the result of adaptation, which compares to PI – RI in the original Vulnerability analyses.

States" and trajectories appear very useful in this context particularly if the management needs to target both the improvement of current situation and the vulnerability to environmental change.

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